The effects of drain types on the seepage control and the stability of retaining walls: a numerical study

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ABSTRACT

One of the most challenging aspects associated with retaining walls is water accumulation behind them and its detrimental effects on wall stability. Water infiltration and seepage cause an increase in pore water pressure, a reduction of effective stress and shear resistance of soil, and can lead to wall failure. In this study, the performance of several types of drainage systems, including in-wall drainage, vertical drainage, inclined drainage systems at angles of 0°, 30°, 45°, and 60° to the horizontal, and drainage beneath the foundation, in controlling seepage and improving the factor of safety of cantilever concrete retaining walls using numerical modeling was investigated and compared with the case without drainage. The study was conducted under two geometric conditions, including level ground behind the wall and sloped ground with an angle of 20°. The results showed that vertical drainage exhibited the best hydraulic performance in seepage control, while horizontal drainage at the wall base provided the greatest improvement in the overall stability factor of safety. Additionally, drainage beneath the foundation performed better in preventing overturning, and 30° inclined drainage showed superior performance in controlling sliding. The comprehensive results of this research demonstrated that a combined approach of seepage and stability analysis is the best tool for selecting appropriate drainage and, in practice, can prevent failures of retaining walls.

KEYWORDS

Different types of drains, seepage and stability analysis, sliding and overturning, GeoStudio software.

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1. Introduction

Rapid urbanization and infrastructure development have increased the need to use land with diverse topographic and hydrological conditions. Retaining walls, as key geotechnical structures, stabilize slopes, protect structures, and control lateral soil movement. A retaining wall is designed to resist lateral soil pressure caused by elevation differences resulting from embankment, excavation, or natural factors. Soil properties, hydrological conditions, and environmental factors play a decisive role in their design and construction. Water flow in the soil behind the wall is one of the most significant factors affecting its performance and stability. Pore-water pressure, combined with lateral soil forces, substantially increases the total load on the wall and can cause failure. Drainage systems are an effective solution for collecting and discharging excess water and preventing hydrostatic pressure behind the wall.

In 1943, Terzaghi first analyzed the effect of water infiltration on lateral soil pressure, incorporating infiltration-induced pore pressure into a wedge-shaped failure analysis [1]. Gray (1958) and Kim (1975) later extended this framework to saturated conditions using mathematical models [2, 3]. Ichihara (1982) experimentally tested these theories using a soil chamber with a retaining wall and a rainfall simulator. Infiltration significantly increased active lateral pressure, which permeable drainage layers could reduce [4]. Lau and Kenney (1984) installed five horizontal drains in a clay slope, which significantly reduced pore-water pressure and improved the factor of safety [5]. Cai et al. (1998) showed through 3D finite element analysis that horizontal drains lower the groundwater level under rainfall; their effectiveness depends on length, spacing, and soil hydraulic properties [6]. Rahardjo et al. (2003) combined field tests and numerical modeling to study horizontal drains in slopes. Drains reduced pore-water pressure and groundwater level, performing better when installed at the lower slope, and the factor of safety increased from 1.1 to 1.5 [7]. Barros (2006) developed a Coulomb-based solution showing that infiltration in saturated cohesionless soil can increase active lateral pressure by up to 30% [8]. Moharrami et al. (2014) numerically showed that horizontal drains in earth dam shells reduce pore-water pressure during rapid drawdown, and that drain number and position strongly affect the factor of safety [9]. Saeed and Irandoost (2015) reported that these drains raised the factor of safety from 1.5 to 1.8 while reducing pore-water pressure and the risk of sliding [10]. Badkheshan and Seifi (2016) showed with SEEP/W that longer horizontal drains significantly reduce seepage, hydraulic gradient, and uplift in earth dams [11]. Rasolitalbar et al. (2016) found that rainfall infiltration raises pore-water pressure and reduces shear resistance, with intensity, duration, and permeability controlling groundwater rise and slope instability [12]. Viswanadham et al. (2017) showed in centrifuge tests that stiffer geogrids and sand drain filters reduce stresses and pore-water pressure, and that combining drainage with stiffer geogrids prevents wall failure [13]. Salmasi et al. (2019) numerically showed that longer, thicker, and more numerous horizontal drains increase the factor of safety under heavy rainfall [14]. Chen et al. (2020) proposed a novel capillary barrier system incorporating a nonwoven geotextile and coarse-grained soil to reduce rainfall infiltration behind retaining walls. Finite element analyses showed that geotextile properties significantly influence water infiltration, matric suction, pore-water pressure, and consequently wall stability [15]. Noori et al. (2021) used SEEP/W and SLOPE/W to show that heavy rainfall is the main driver of pore-pressure rise, that lower-wall drains are most effective, and that in fine-grained soils, vertical drains outperform horizontal ones [16]. Jayanandan and Viswanadham (2024) experimentally investigated hybrid geosynthetic-reinforced soil walls subjected to rainfall using a geotechnical centrifuge. Incorporating a drainage layer and high-transmissivity geosynthetics effectively reduced pore-water pressure and wall deformation, improving both hydraulic and stability performance [17].

Previous research demonstrates that drainage is important for controlling water-related effects in retaining walls and other soil structures; however, comprehensive comparative investigations of different drain types and their relative performance remain limited. Therefore, this study evaluates the performance and effects of various drainage configurations on seepage control and the stability of retaining walls. Initially, a baseline retaining-wall model was created in SLOPE/W under dry conditions, where the soil behind the wall is assumed to be without water flow, and the initial factor of safety was calculated. Subsequently, water flow was simulated in SEEP/W, and the results were transferred to SLOPE/W to determine the reduction in the factor of safety due to water. Furthermore, different drainage scenarios, including vertical drainage, inclined drainage, and drainage beneath the foundation, were incorporated into the model and analyzed. The models were investigated under two geometric conditions: level ground and sloped ground above the wall (20°). In all models, changes in pore-water pressure, discharge, and factor of safety were evaluated, and a comprehensive comparison was made among the scenarios. The findings provide a practical basis for selecting effective drainage configurations under different ground-surface conditions.

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2. Methodology

2.1. Numerical Modeling

SEEP/W model from the GeoStudio software is designed for simulating water flow in porous media and is based on the finite element method. This software is capable of simulating both steady-state and transient seepage. It predicts the path of water movement, seepage discharge rate, and the distribution of pore water pressure throughout the entire simulation domain. The SLOPE/W model is another subgroup of the GeoStudio software and is designed for slope stability analysis based on the limit equilibrium method. This model calculates the slope stability safety factor by solving force and moment equilibrium equations.

2.2. Validation of Numerical Model

For software validation, a homogeneous earth dam physical model that was conducted by Kohpeyma et al. in 2019 [18] was used with similar geometric, hydraulic, and boundary conditions. The dam height was 49.5 cm, the upstream and downstream water levels were 48.5 cm and 4 cm, respectively, and the dam body soil was sandy clay (as shown in Figure 1). The model mesh size was selected as 1 cm. Results of the model after reaching steady-state conditions, including piezometric head at 11 locations, were extracted and compared with laboratory data (as shown in Figure 2). The difference in data was less than 10 percent, and the root mean square error index was 8.47 percent, indicating appropriate accuracy of the model in simulating the seepage phenomenon.

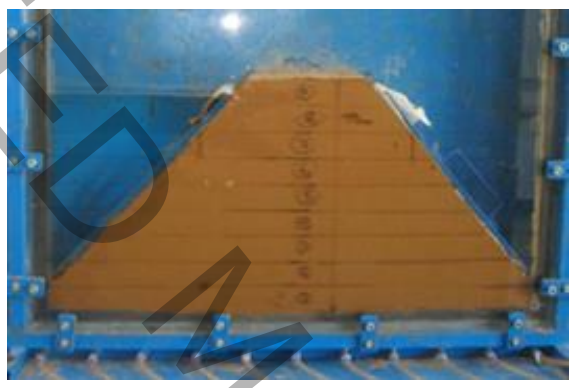


Figure 1. Physical model of the homogeneous earth dam in the study by Kohpeyma et al. (2019) [18]

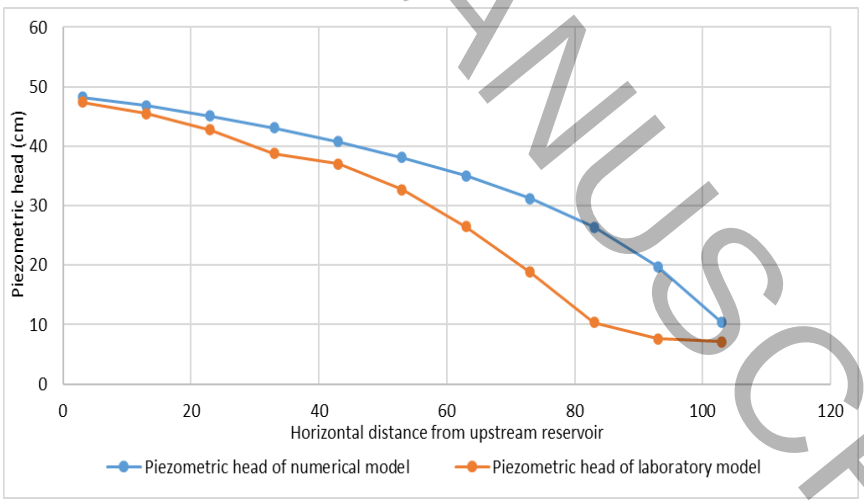


Figure 2. Comparison of piezometric head between numerical and laboratory models in the study by Kohpeyma et al. (2019) [18]

For validation of the SLOPE/W numerical model, the soil slope example from the study by Kilanehei et al. in 2017 [19], with a height of 10 meters and a slope of 3:2, was used (as shown in Figure 3). Soil properties were considered according to the Mohr–Coulomb criterion and the reference data. The analysis was performed using the Bishop, Janbu, and Morgenstern–Price methods, and the calculated factors of safety (Table 1) exhibited very little difference compared to the results of the reference study, which demonstrates the high accuracy of the numerical model in simulating the behavior of soil slopes.

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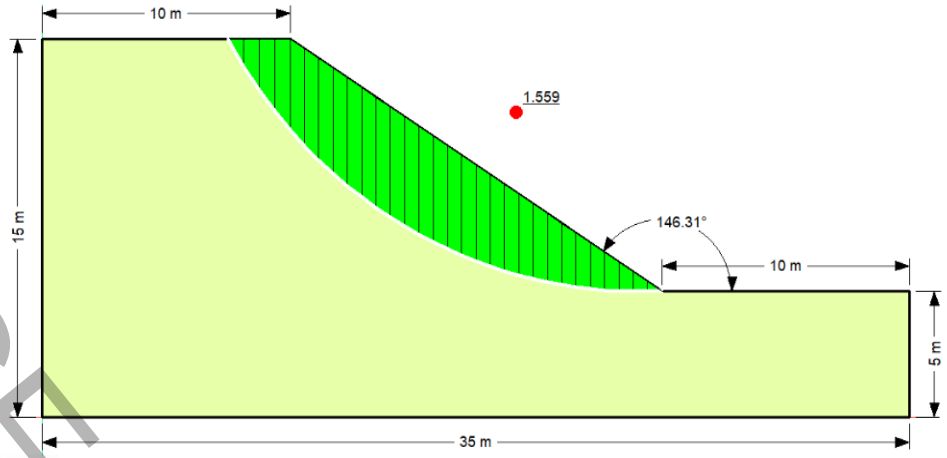


Figure 3. Evaluation model for slope stability using the Bishop method

Table 1. Comparison of safety factors in the study by Kilanehei et al. (2017)

Analysis Method	Bishop	Janbu	Morgenstern–Price
Factor of Safety (Kilanehei et al.)	1.56	1.47	1.55
Factor of Safety (this study)	1.55	1.46	1.55

2.3. Specifications of the models

The process of numerical modeling was carried out in four main stages, including definition of model geometry, meshing, definition of material properties, and boundary conditions. The geometry of the models was developed progressively; at first, the retaining wall was defined as a cantilever T-shaped structure with a vertical height of 10 meters, a wall thickness of 1 meter, a footing thickness of 1 meter, and a footing width of 7 meters [20-22]. To investigate the performance of the drainage systems, an in-wall drainage system with a thickness of 20 centimeters [20], as well as vertical drains, inclined drains, and drains beneath the foundation within the soil with a thickness of 50 centimeters and a length of 10 meters, were added to the model. Initially, the model consisted only of soil and wall in dry conditions, and in subsequent stages, it was completed with the addition of the groundwater level and drainage systems. The geometry of the retaining wall and various drainage types are presented in Figures 4 and 5, respectively. For numerical solution, the model was subdivided into a mesh of irregular triangular elements with an average size of approximately 1 meter. To increase accuracy in regions near the drains and wall, finer mesh dimensions were selected; specifically, approximately 0.2 meters for the in-wall drain and approximately 0.3 meters for the vertical drains, inclined drains, and drains beneath the foundation. To ensure grid independence, mesh convergence analysis was performed, which showed that no significant changes in results occurred with finer meshing. The results of mesh sensitivity analysis are presented in Table 2. Materials were classified into three categories: retaining wall, soil behind the wall, and drainage systems. The soil behind the wall was classified as SC (clayey sand) according to the Unified Soil Classification System (USCS), whereas the drainage material was represented by granular gravel. The wall was modeled as an impermeable structure; the soil behind the wall and drainage systems were defined in saturated conditions. The hydraulic properties of the materials are presented in Table 3 [23-26]. For steady-state flow analysis, boundary conditions were defined such that at the upstream boundary, constant total head or zero water pressure is applied; at the downstream boundary, a specified total head is considered; and the drainage outlets are defined with a zero-pressure condition to provide the possibility of free drainage.

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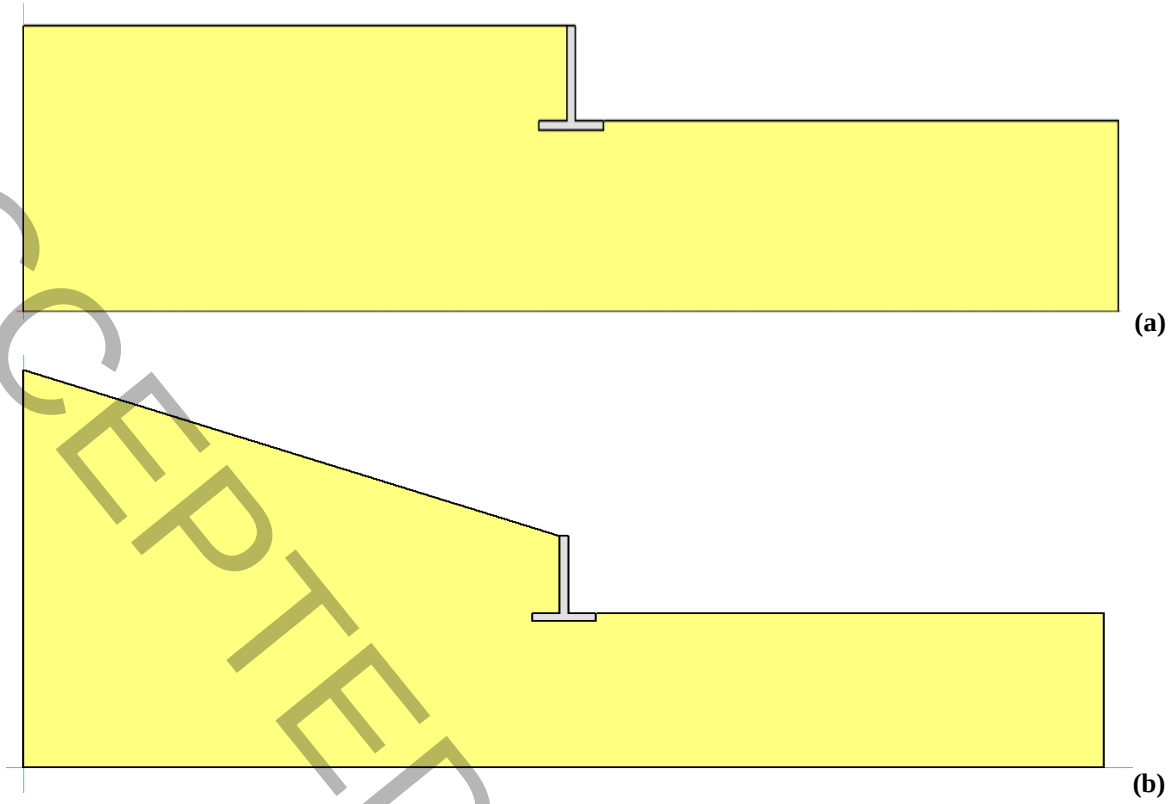
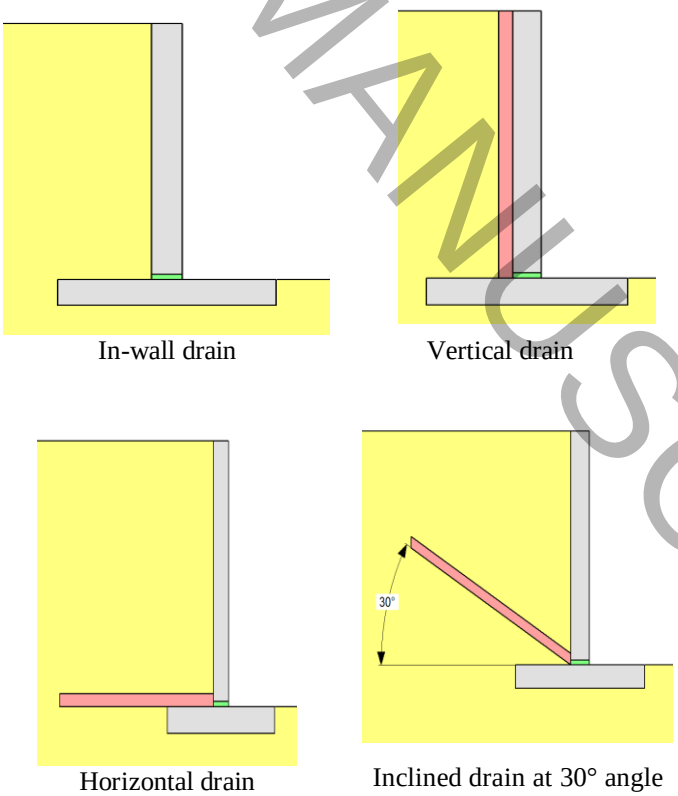
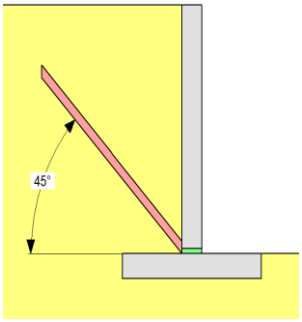


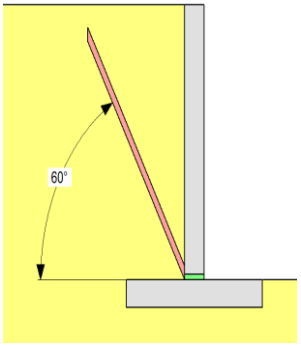
Figure 4. Retaining wall model, a) flat backfill b) sloped backfill



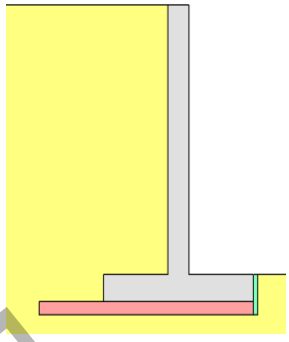
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Inclined drain at 45° angle



Inclined drain at 60° angle



Drain beneath the foundation

Figure 5. Types of drainage systems investigated in this study

Table 2. Results of Mesh Sensitivity Analysis

Mesh Size (m)	2	1	0.5
Pore Water Pressure (kPa)	62.075	62.247	62.426
Discharge Rate (m^3/s)	7.27E-07	7.16E-07	7.16E-07

Table 3. Hydraulic Properties of Materials [23-26]

Parameters	Retaining Wall	Soil	Drainage Systems
Saturated Water Content	—	0.38	0.3
K_{sat} (m/s)	—	10^ (-6)	10^ (-4)
K_Y/K_X	—	0.1	1
Unit Weight (kN/m^3)	24	18	18
Internal Friction Angle (°)	5	28	45
Cohesion (kPa)	15000	30	0

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2.4. Overturning and sliding safety factors

The factor of safety against overturning was calculated using the results of the seepage analysis from SEEP/W software. For this purpose, reference points were defined at the wall height, footing height, footing length, and wall heel length, and pore water pressure at all these locations was extracted from SEEP/W software. By analyzing the pore water pressure data and plotting pore water pressure distribution diagrams, the necessary parameters for stability calculations were provided. To determine the soil pressure behind the wall, for the same points where pore water pressure was determined, the total and effective vertical stresses were calculated using Equations 1 and 2. To calculate the lateral soil pressure, first, the active Rankine pressure coefficient was determined for the level ground and sloped ground behind the wall using Equations 3 and 4, respectively. Subsequently, the lateral soil pressure was calculated from Equation 5. By plotting soil pressure distribution diagrams, the total soil force value was also determined. Finally, the factor of safety against overturning was calculated from Equation 6 [21-22]. Figure 6 shows schematically the resisting and overturning forces acting on the wall.

$$\sigma_v = z \times \gamma \quad (1)$$

$$\sigma'_v = \sigma_v - u \quad (2)$$

$$K_a = \frac{1-\sin\varphi}{1+\sin\varphi} \quad (3)$$

$$K_a = \cos\alpha \times \frac{\cos\alpha - \sqrt{\cos^2\alpha - \cos^2\varphi}}{\cos\alpha + \sqrt{\cos^2\alpha - \cos^2\varphi}} \quad (4)$$

$$\sigma'_a = K_a \times \sigma'_v \quad (5)$$

$$FS_{overturning} = \frac{\sum M_R}{\sum M_O} \quad (6)$$

In the above equations, z is the depth from the ground surface, γ is the unit weight of soil, u is pore water pressure, φ is the internal friction angle of soil, α is the slope angle of the soil surface, K_a is the Rankine's active pressure coefficient, σ_v is the vertical stress, σ'_v is the effective vertical stress, σ'_a is the lateral soil pressure, $\sum M_R$ is the sum of resisting moments, and $\sum M_O$ is the sum of overturning moments.

The factor of safety against sliding was also calculated using the results of the seepage analysis from SEEP/W software. The procedure and steps for calculating this factor are similar to the method for calculating the factor of safety against overturning and were based on the same principles. The factor of safety against sliding was calculated from Equations 7 and 8.

$$FS_{sliding} = \frac{\sum F_R}{\sum F_d} \quad (7)$$

$$FS_{sliding} = \frac{\sum V \times \tan\varphi_2 + B \times C_2 + P_p}{P_a \times \cos\alpha} \quad (8)$$

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In the above equations, ΣF_R is the sum of resisting horizontal forces, ΣF_d is the sum of overturning horizontal forces, ΣV is the sum of vertical forces, φ is the internal friction angle of soil beneath the footing, B is the length of the wall footing, C_2 is the cohesion of soil beneath the footing, P_p is the horizontal passive force, P_a is the horizontal active force, and α is the slope angle of the soil surface.

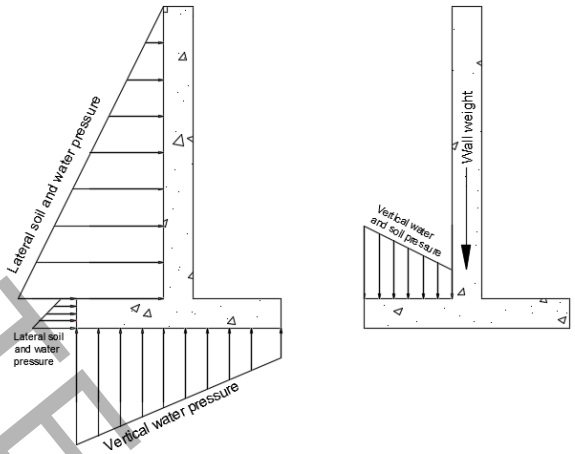


Figure 6. Schematic representation of resisting and overturning forces in the stability analysis of retaining walls

3. Results and Discussion

3.1. Seepage Analysis and Investigation of Hydraulic Performance

Numerical modeling of five primary scenarios was conducted, including the reference case without drainage, in-wall drainage, vertical drainage, inclined drains (at angles of 0°, 30°, 45°, and 60° to the horizontal), and drainage beneath the foundation for two geometric conditions of the soil behind the wall (level ground and sloped ground at 20°) using SEEP/W software, and the seepage analysis results were extracted. For example, Figure 7 presents the analyzed model for the vertical drainage case. The analysis criterion was selected as the total discharge passing through two sections below the footing and the outlet of the in-wall drainage. For comparison, the efficiency ratio of each case was calculated as the total discharge of that case divided by the total discharge in the case without drainage, and the results are presented in Figures 8 and 9. It should be noted that the types of models are listed in Table 5.

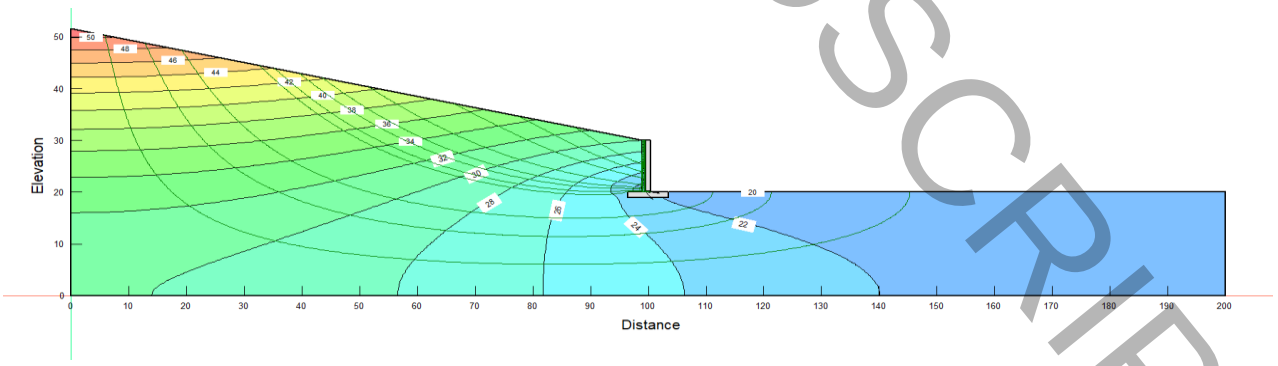


Figure 7. Vertical drain seepage analysis results in SEEP/W

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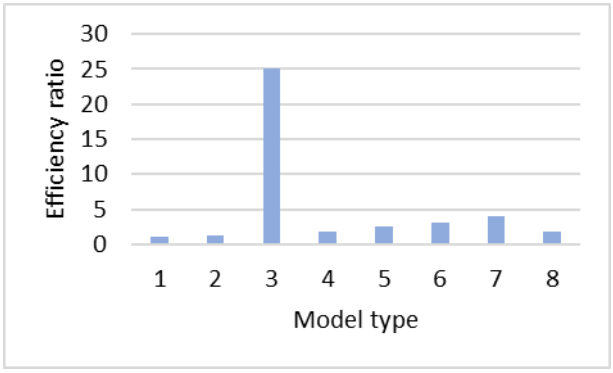


Figure 8. Efficiency ratio of various drainage configurations with level ground behind the wall

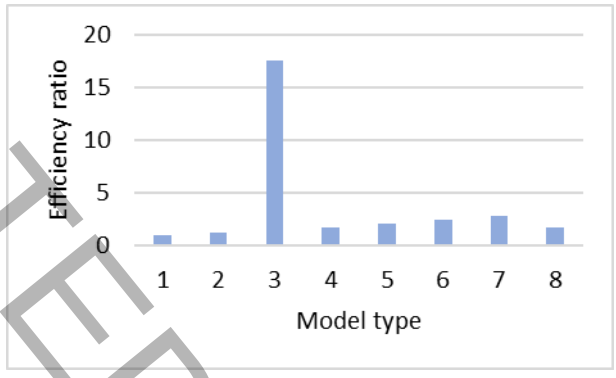


Figure 9. Efficiency ratio of various drainage configurations with sloped ground behind the wall

For level ground, the vertical drain provided the highest efficiency ratio, with the total monitored discharge being approximately 25 times that of the corresponding reference case without drainage; moreover, more than 95% of the total monitored discharge exited through the vertical drain. This superior hydraulic performance can be attributed to the geometry of the vertical drain, which extends over the entire height of the backfill. Compared with the other configurations, it provides a larger effective drainage area and greater contact with the surrounding soil, allowing it to cut across more flow lines and direct a larger portion of the seepage toward the drainage outlet. As shown in Figure 7, the vertical drain substantially changes the flow paths by directing water toward the outlet and reducing the continuation of flow beneath the footing. The vertical drain therefore performs better not simply because of the discharge through its outlet, but because its full-height arrangement enables it to intercept and redirect a greater portion of the seepage. The inclined drains also performed favorably, with efficiency increasing continuously from 0° to 60°. This trend can be attributed to their increasing vertical reach, which allows them to cut across a greater portion of the flow paths. For the 20° sloped ground, the overall ranking remained similar, although the efficiency ratio of the vertical drain decreased to approximately 17.6. Because each ratio was normalized by its corresponding reference case, this decrease does not necessarily indicate a lower absolute discharge than under level-ground conditions. Reducing the vertical-drain thickness from 50 to 40 cm caused a slight decrease in efficiency, whereas reducing it to 10 cm produced a more substantial decline. Nevertheless, the 10-cm drain still outperformed the in-wall and beneath-foundation drains. Overall, the results indicate that drain arrangement and thickness affect hydraulic performance. The selection of a drainage configuration should therefore consider its ability to redirect seepage effectively, together with its implications for overall, sliding, and overturning stability.

3.2. Overall Factor of Safety

To investigate the effect of water presence and seepage and the efficiency of various drainage types on the stability of the retaining wall, initially, the reference model without drainage was modeled under dry conditions and without water flow, and the overall factor of safety was calculated using the Bishop method. Subsequently, the seepage analysis results and pore water pressure outputs from SEEP/W software were transferred to SLOPE/W to apply the effect of water flow and pore water pressure to the model, and the factor of safety was recalculated. Table 4 presents the values of the overall factor of safety and the magnitude of its reduction.

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It is observed that in the case of level ground behind the wall, the factor of safety decreased from 2.43 under dry conditions to 1.62 under seepage conditions, representing a decrease of approximately 33.16% (due to an increase in pore water pressure and seepage). In the case of sloped ground, this effect is amplified, and the factor of safety decreased from 2.91 under dry conditions to 1.40 under seepage conditions, representing a decrease of approximately 52.01%, indicating the higher sensitivity of the sloped ground model to the presence of water. After confirming the negative effect of water, a series of drainage scenarios was added individually to the model, and the percentage change in the factor of safety relative to the seepage case without drainage was determined. Tables 5 and 6 present the improvement in the overall factor of safety with the addition of drains. Figure 10 shows, for example, the analyzed model of the vertical drain case.

Table 4. Overall Factor of Safety Values and Magnitude of Reduction with Level and Sloped Ground behind the Wall

Model Type	Overall Factor of Safety	Change Value (%)
Level Ground		
1. Without drainage (completely dry soil)	2.43	0
2. Without drainage (completely saturated soil)	1.62	-33.16
Sloped Ground		
1. Without drainage (completely dry soil)	2.91	0
2. Without drainage (completely saturated soil)	1.4	-52.01

Table 5. Effect of Drains on Overall Factors of Safety with Level Ground behind the Wall

Model Number	Model Type	Overall Factor of Safety	Change Value (%)
1	Without drainage	1.62	0
2	in-wall drainage	1.71	5.66
3	vertical drainage	1.8	11
4	inclined drainage (0°)	1.95	20.41
5	inclined drainage (30°)	1.92	17.82
6	inclined drainage (45°)	1.91	17.09
7	inclined drainage (60°)	1.89	16.04
8	drainage beneath the foundation	1.93	18.87

Table 6. Effect of Drains on Overall Factors of Safety with Sloped Ground behind the Wall

Model Number	Model Type	Overall Factor of Safety	Change Value (%)
1	Without drainage	1.4	0
2	in-wall drainage	1.51	8.17
3	vertical drainage	1.64	17.49
4	inclined drainage (0°)	1.81	29.75
5	inclined drainage (30°)	1.79	28.24
6	inclined drainage (45°)	1.78	27.6
7	inclined drainage (60°)	1.76	25.95
8	drainage beneath the foundation	1.74	24.88

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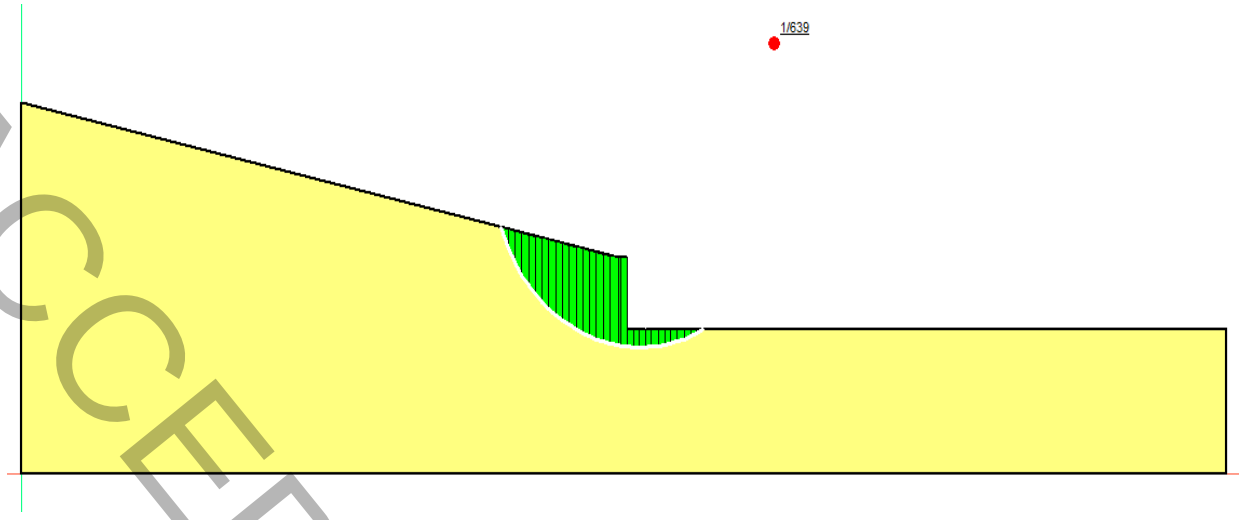


Figure 10. Results of overall stability analysis for vertical drain case with sloped ground

The results demonstrate that all drainage configurations improve the factor of safety, although the degree of improvement varies. For level ground (Table 5), the factor of safety increases from 1.62 in the baseline seepage condition to 1.71 with the in-wall drain, 1.80 with the vertical drain, and 1.93 with drainage beneath the foundation. The horizontal drain (0°) provides the greatest improvement, increasing the factor of safety to 1.95 (approximately 20.41%). This superior performance can be explained by considering the interaction between the direction of seepage forces, effective stress, and soil shear resistance. Seepage forces act in the direction of water flow. When seepage is directed downward, the seepage force acts in the same direction as gravity and contributes to an increase in effective stress. The resulting increase in effective stress enhances the available shear resistance of the soil and can consequently improve stability along potential failure surfaces. In contrast, when the direction of seepage is inclined, the downward component of the seepage force becomes smaller as the flow direction deviates from the vertical. Thus, the beneficial contribution of downward seepage to effective stress and shear resistance is reduced. Under the conditions examined in this study, the horizontal-drain configuration produces a more favorable seepage pattern, resulting in the greatest improvement in overall stability.

For sloped ground (Table 6), the same trend is observed: the factor of safety increases from 1.40 in the baseline case to 1.81 with the horizontal drain, corresponding to an improvement of approximately 29.75%. Although the absolute factors of safety are lower than those for level ground, the relative improvement is greater. This indicates that the horizontal drain remains the most effective configuration for improving stability under the investigated conditions. Overall, these results highlight that drainage effectiveness depends not only on the amount of water discharged but also on the direction of seepage forces and their influence on effective stress and soil shear resistance along potential failure surfaces.

3.3. Overturning Safety Factor

To investigate the factor of safety against overturning, the pore water pressure results obtained from the numerical model were used. Table 7 presents the values of the overturning factor of safety and the magnitude of its reduction. Tables 8 and 9 present the improvement in the factor of safety against overturning with the addition of various drainage systems.

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Table 7. Overturning Factor of Safety Values and Magnitude of Reduction with Level and Sloped Ground behind the Wall

Model Type	Overturning Factor of Safety	Change Value (%)
Level Ground		
1. Without drainage (completely dry soil)	3.05	0
2. Without drainage (completely saturated soil)	1.3	-57.58
Sloped Ground		
1. Without drainage (completely dry soil)	2.99	0
2. Without drainage (completely saturated soil)	1.16	-61.12

Table 8. Effect of Drains on Overturning Factors of Safety with Level Ground behind the Wall

Model Number	Model Type	Overturning Factor of Safety	Change Value (%)
1	Without drainage	1.3	0
2	in-wall drainage	1.43	10.5
3	vertical drainage	1.97	52.43
4	inclined drainage (0°)	2.12	63.4
5	inclined drainage (30°)	2.15	66.33
6	inclined drainage (45°)	2.12	64.02
7	inclined drainage (60°)	2.08	60.93
8	drainage beneath the foundation	2.21	70.5

Table 9. Effect of Drains on Overturning Factors of Safety with Sloped Ground behind the Wall

Model Number	Model Type	Overturning Factor of Safety	Change Value (%)
1	Without drainage	1.16	0
2	in-wall drainage	1.29	10.83
3	vertical drainage	1.93	66.07
4	inclined drainage (0°)	1.96	68.64
5	inclined drainage (30°)	2.12	81.87
6	inclined drainage (45°)	2.09	79.64
7	inclined drainage (60°)	2.06	76.72
8	drainage beneath the foundation	2.16	85.4

It is observed that in the case of level ground behind the wall, the factor of safety decreased from 3.05 under dry conditions to 1.30 under flowing conditions (57.58% reduction). With the addition of drains, the factor of safety increases significantly; in this case, the best performance is obtained with drainage beneath the foundation with a factor of safety of 2.21 (70.50% increase). In the case of sloped ground, the factor of safety decreased from 2.99 under dry conditions to 1.16 under flowing conditions (61.12% reduction), and again, the greatest improvements are associated with the drainage beneath the foundation model (85.40% increase). Therefore, it is concluded that the installation of drains, particularly drainage beneath the foundation, can significantly increase the factor of safety against overturning.

3.4. Sliding Factor of Safety

To investigate the factor of safety against sliding, the pore water pressure results obtained from the numerical model served as the basis for calculations, and the values of the factor of safety against sliding were calculated under dry and flowing conditions in the model without drainage (Table 10). Subsequently, the effect of adding various drainage types on the factor of safety against sliding (Tables 11 and 12) was examined.

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Table 10. Factor of Safety against Sliding and Magnitude of Reduction with Level and Sloped Ground Behind the Wall

Model Type	Sliding Factor of Safety	Change Value (%)
Level Ground		
1. Without drainage (completely dry soil)	1.82	0
2. Without drainage (completely saturated soil)	0.85	-52.92
Sloped Ground		
1. Without drainage (completely dry soil)	1.71	0
2. Without drainage (completely saturated soil)	0.73	-57.24

Table 11. Effect of Drains on Factors of Safety against Sliding with Level Ground behind the Wall

Model Number	Model Type	Sliding Factor of Safety	Change Value (%)
1	Without drainage	0.85	0
2	in-wall drainage	0.99	16.26
3	vertical drainage	1.37	59.65
4	inclined drainage (0°)	1.41	64.33
5	inclined drainage (30°)	1.44	68.66
6	inclined drainage (45°)	1.43	67.25
7	inclined drainage (60°)	1.41	65.38
8	drainage beneath the foundation	1.3	52.94

Table 12. Effect of Drains on Factors of Safety against Sliding with Sloped Ground behind the Wall

Model Number	Model Type	Sliding Factor of Safety	Change Value (%)
1	Without drainage	0.73	0
2	in-wall drainage	0.86	17.53
3	vertical drainage	1.29	76.03
4	inclined drainage (0°)	1.27	73.43
5	inclined drainage (30°)	1.36	86.58
6	inclined drainage (45°)	1.35	85.07
7	inclined drainage (60°)	1.34	83.15
8	drainage beneath the foundation	1.23	68.08

In the case of level ground behind the wall, the factor of safety against sliding decreased from 1.82 under dry conditions to 0.85 under flowing conditions (52.92% reduction). With the installation of drains, the sliding safety factor increases significantly, and the 30° inclined drain with a factor of safety of 1.44 (68.66% increase) demonstrates the best performance. This superior performance can be attributed to the favorable redistribution of seepage and the reduction in pore-water pressure and uplift beneath the foundation. These effects increase the effective normal force and the resulting frictional resistance along the foundation interface, thereby improving the factor of safety against sliding. In the case of sloped ground behind the wall, the factor of safety decreased from 1.71 under dry conditions to 0.73 under flowing conditions (57.24% reduction); however, with the installation of drains, the factor of safety improves, and again the 30° inclined drain with a factor of safety of 1.36 (86.58% increase) has provided the best result. Overall, it is observed that the installation of drains significantly improves the factor of safety against sliding. In both geometric conditions, inclined drains at 30° have had the greatest effect, and the overall effectiveness in the sloped ground case is generally greater than in the level ground case.

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4. Conclusions

The presence and flow of water behind retaining walls is one of the most significant factors reducing stability and threatening the useful life of the structure, and the absence of a proper drainage system can lead to a significant reduction in safety factors. The numerical analyses conducted in this research on a 10-meter cantilever concrete retaining wall in soil with assumed sandy clay properties using SEEP/W and SLOPE/W software demonstrate that the type and location of the drain play a decisive role in seepage control and stability. The results, in summary, showed that:

1. The vertical drain exhibited the highest hydraulic efficiency, increasing the total monitored discharge to approximately 18–25 times that of the corresponding case without drainage, depending on ground-surface geometry. For inclined drains, hydraulic efficiency increased with the inclination angle.
2. The horizontal drain at 0° provided the greatest improvement in overall stability, increasing the factor of safety under seepage conditions by approximately 20–30%, depending on ground-surface geometry.
3. Drainage beneath the foundation provided the greatest improvement against overturning, increasing the corresponding factor of safety by approximately 70–85%, depending on ground-surface geometry.
4. The 30° inclined drain produced the greatest improvement against sliding, increasing the corresponding factor of safety by approximately 69–87% under the investigated ground conditions.
5. The results obtained from the conducted analyses highlight the importance of selecting the type and location of drainage appropriate to the design objective. Therefore, depending on which of the instability conditions—overall instability, overturning, or sliding—is critical, or whether water management and drainage of accumulated water behind the wall is decisive, an appropriate drain can be designed and implemented.
6. Comparison of level and sloped ground conditions behind the wall showed that in the sloped case, the structure's sensitivity to water presence is greater and the reduction of safety factors is more severe; however, at the same time, the magnitude of improvement resulting from drain installation is also more significant.

The comprehensive results of this research demonstrate that a combined approach of seepage and stability analysis is the best tool for selecting appropriate drainage and, in practice, can prevent failures of retaining walls. Furthermore, relying solely on a single criterion, such as seepage reduction or improvement of the safety factor, is insufficient, and a set of criteria must be simultaneously considered in drainage design.

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